UMAN TOLERANCE TO ABRUPT ACCELERATIONS:
A SUMMARY OF THE LITERATURE

Dynamic Science Report 70-13

DYNAMIC SCIENCE

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By

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ABSTRACT

This report summarizes the history and research and associated problems in investigation of human abrupt accelerations. Enumeration of possible impact injury follows discussion of the five parameters of human tolerance. Tolerable levels of acceleration impact were extracted from current literature.

Written as a text for aviation safety personnel, principally physicians and engineers involved in crash survival design, the tone of this report assumes that each person has limited knowledge of the other's discipline. The material is currently taught at the Crash Survival Investigator's School conducted by Dynamic Science, "The AvSER Facility," in Phoenix.

ACKNOWLEDGEMENTS

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Chapter 1

THE PROBLEM

> Impacts involving the human body are among the common phenomena of life. From the buttocks slap which is often used to start the breathing of a new born baby, to the fatal fall, which may occur at practically any age, impact may be said to be a part of human experience from birth of death. As man's mode of life has become progressively mechanized, impact hazards have increased both in number and magnitude. [15:48]

The hazards man encounters during a sudden positive or negative acceleration and the body's reaction to the causitive forces are subjects of this paper. More specifically, we are interested in what forces the human riding in a moving vehicle can sustain without incapacitating injury to this human during rapid acceleration. Just as the catcher uses a padded glove to absorb energy of the pitcher's speedy throw, so vehicles can be designed to protect occupants during impacts. If the engineer designing a vehicle knows what the human body's design limits are and can forecast the vehicle's maximum accelerative forces, he can realistically design devices to absorb much of the energy of impact upon a vehicle before injurious energy reaches the vehicle's occupants. The catcher does not want excess weight to impair his playing nor does the aircraft user want excess weight to protect the occupant because excess weight sacrifices aircraft performance. Hence, if the

design engineer knows what energy level the human occupant can sustain without incapacitation, the engineer can design force attenuation devices to that level, and not beyond.

I do not want to imply that upon impact, which is an abrupt acceleration, that an aircraft is expected to maintain its integrity to fly again another day. In fact, structural collapse of an aircraft is itself energy attenuation. If the aircraft structure surrounding the occupant collapses and the occupant is not incapacited then the designer has done his job. Obviously, there is a limit to energy attenuation devices that can be installed between the airframe and occupant.

As previously stated, it is not necessary to design aircraft structurally stronger than the occupant, for even if the aircraft collapses but does not impinge upon the occupant's immediate area and strike him, it is still possible to transmit energy from the airframe to the occupant to cause fatal internal injuries. For high impact forces it matters not whether the structure or transmitted forces kill the occupant. This explanation clarifies my statement that the engineer does not need to design beyond the structural limits of the human.

However, the chance of overdesign is remote. Very few aircraft structural and occupant restraint strengths approach the human injurious limits [32:1]. Some crop dusters and Navy fighter aircraft built for speed, maneuverability, and especially hard carrier operations, approach

optimum strength. Man has a strong and tough body.

In order that the design engineer and aviation physician can understand man's reactions to rapid acceleration this paper presents historical highlights of, problems encountered in, and terminology associated with acceleration research. Moreover, there is an extensive discussion of parameters of human tolerance and some idea of man's structural limits in impact.

Chapter 2

RESEARCH

Because of vertebral injuries sustained by trainee pilots during glider accidents in the early 1940's German scientists investigated the impact effects on their pilots and established vertebral impact limits which are still valid today. This was the first time high magnitude, short duration accelerations had become a defined problem [31].

Introduction of ejection seats for high speed aircraft opened the field of research further into human response in headward accelerations. After the war research in Britain culminated in the design of the Martin-Baker ejection seat [44:5]. Over the past three decades other pioneers, such as DeHaven, Stapp, Swearingen, Beeding, and von Gierke have contributed to this new field of research.

One of the biggest research problems is selecting test specimens. Since this paper is written to define human tolerance it would be best if humans were used to evaluate this tolerance. However, obviously humans cannot be used in injurious levels and hence very little subjective endpoint data is available. Humans can be used to certain non-injurious levels and values interpolated for hypothetical injurious levels. Those who have been used are generally young males, well fit, armed forces personnel, who are

expecting an impact [46:2]. Even using this narrow test specimen there are physical and behaviorial variations of the subjects. Moreover, this testee definition is not representative of the human cross section for which an engineer wants to design an aircraft.

Accidental injuries to humans are valuable but are not repeatable for verification. Damage can be assessed but determination of accurate force vectors which caused the trauma is very difficult at best. Moreover, the investigation is only as good as the investigator is competent. This argument is not intended to discourage complete investigations of injuries to determine forces which caused the injuries. In fact, the investigator, whether or not he is a physician, should ask pathologists for a report on all truama and not just that which caused death. Normally, aviation pathologists will furnish this information as a routine procedure. Information obtained this way adds to aviation medicine's knowledge of acceleration injuries.

When a human foresees an impending impact his muscles may tighten and hence offer some support for internal organs. Obviously cadavers do not have this physiological reaction but are limited to mechanical failure. Moreover, cadavers are usually diseased and worn out and are not structurally as good for impact testing as some people think. Results must be treated with caution [31:28].

Animals, whether sedated or not, will not have pre-impact reactions unless they are aware of their environment. Also, since animals have different anatomical geometry, a problem when testing is to determine those structurally closest to humans and then reliably extrapolating from animals to man.

Anthropormorphic means "like a human". Anthropormorphic dummies are often used but these devices cannot give physiological responses and do not act dynamically like people. Analog computers are valuable but controversial because human behavior is nonlinear. The best subjects are humans but researchers often use animals and cadavers and then empirically define human tolerance levels [41]. Snyder illustrates different methods of studying impact in Figure 1.

High amplitude accelerations of short duration cannot be produced on human centrifuges which are limited to rates of onset of the order of 3 to 20 G/second. Drop towers rocket sleds, and ejection seats are a few of the facilities used in impact research shown in Figure 2.

Another factor that clouds impact acceleration literature is determing where measurements are taken [20]. Should accelerometers be secured to the vehicle, seat, subject, or all three? Often the literature fails to indicate where pulse data is obtained. Accelerations on the head are far different from chest data; moreover, instrumenting

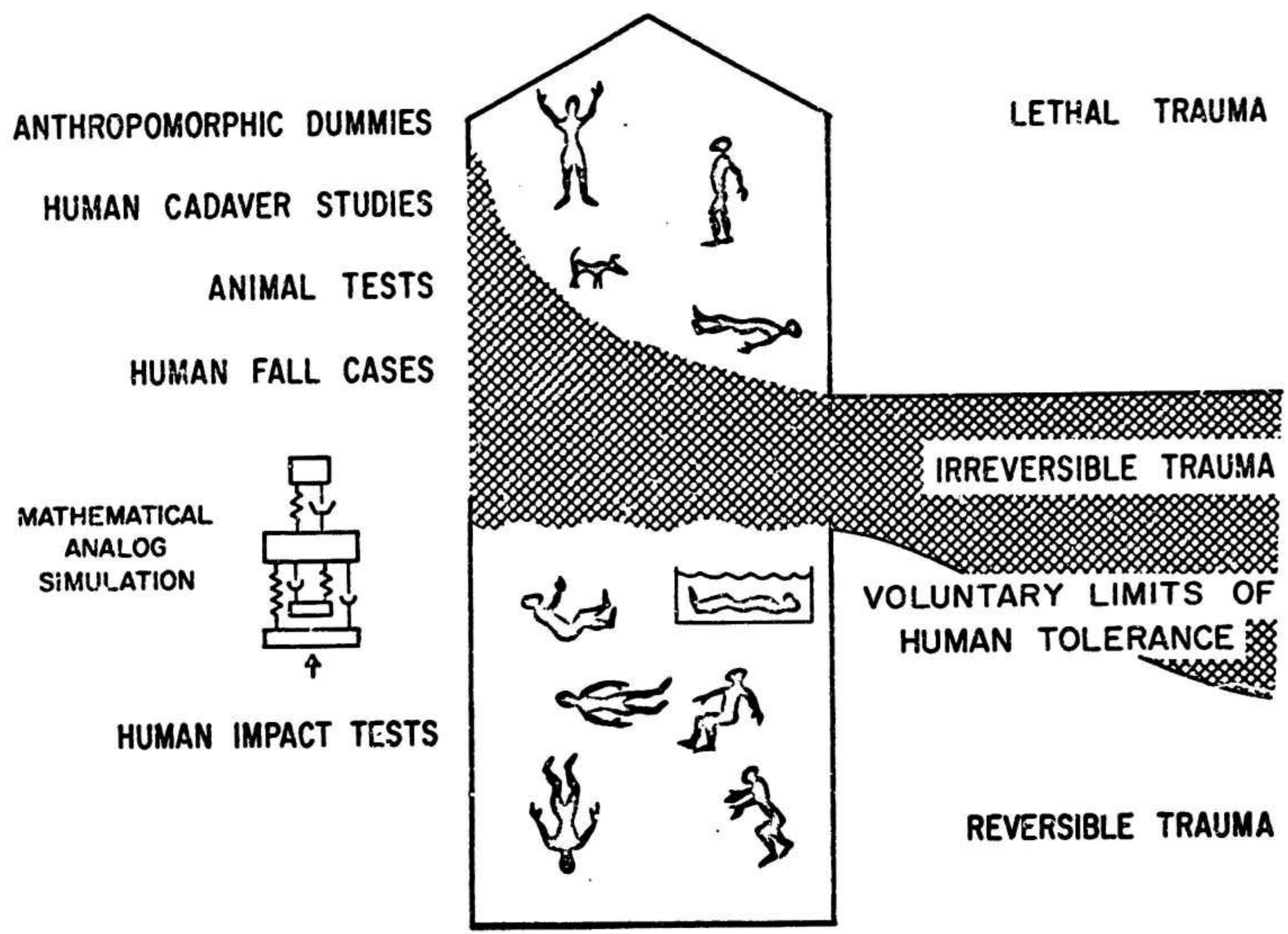


Figure 1

Methods of Determining Human Impact Tolerance [37]

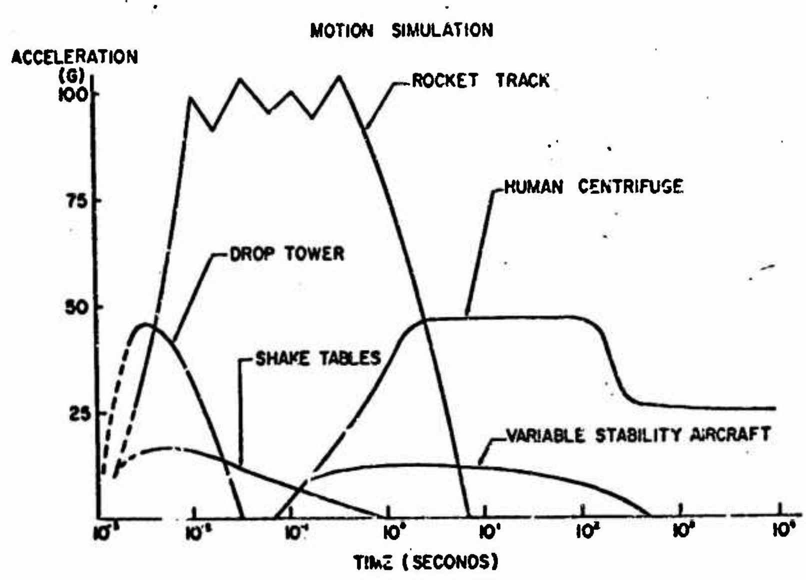


Figure 2

Ranges of Time and Acceleration Obtainable
With Certain Devices [14]

people is difficult but getting better. This uneasiness with accelerometers has led some investigators to use high speed cinematography to assist in their analysis [1:17].

Traces obtained by accelerometers are not easily interpreted due to lack of established procedures. Figure 3 is a typical trace obtained by dropping a human in a B-58 capsule. Figure 4, 5, and 6 illustrate possible methods of interpreting, each of which would give entirely different results [20:7]. Of the three methods Figure 6 is probably the most valid.

Researchers themselves are different. Engineers consider accelerations an engineering study while physicians state it lies within their discipline. Mathematicians want solutions to follow from an equation [24:4]. Endeavors in impact acceleration research lie not within one area but overlap into several.

> There have been cases where engineers have attempted to do acceleration research delving dangerously into medical areas. However, there have been, perhaps, more cases of medical scientists doing impact acceleration research delving equally dangerously into the field of dynamics without adequate support of training.[21]

> It is the writer's opinion, shared generally by the Aerospace Industry, that impact acceleration is a dynamic problem that cannot be solved solely by the medical profession. Neither can it be solved solely by the engineers. Great accomplishments can only be achieved by competent teams made up of several disciplines, the most important of which are medical sciences, mathematical dynamics, and engineering. [21]

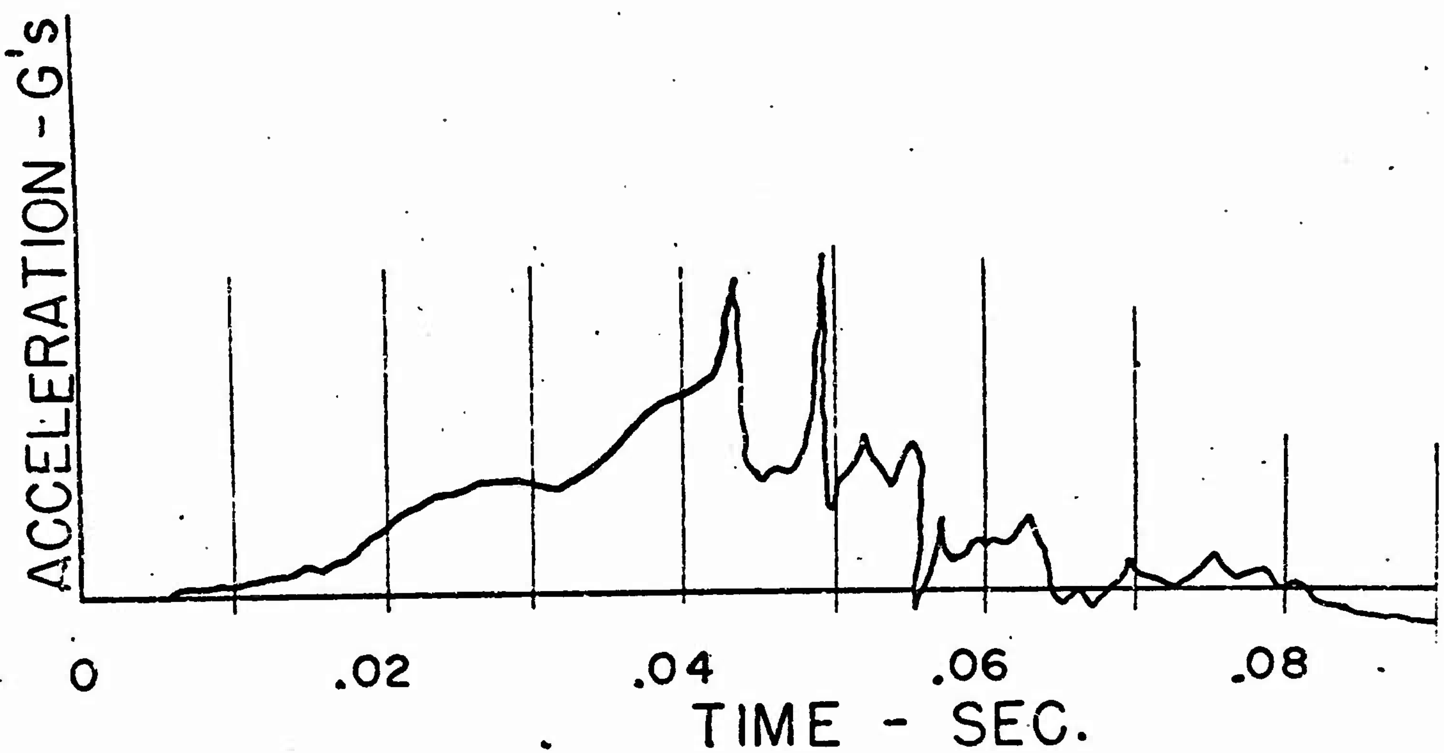


Figure 3

Typical Acceleration Trace Measured On Subject's Sternum [20]

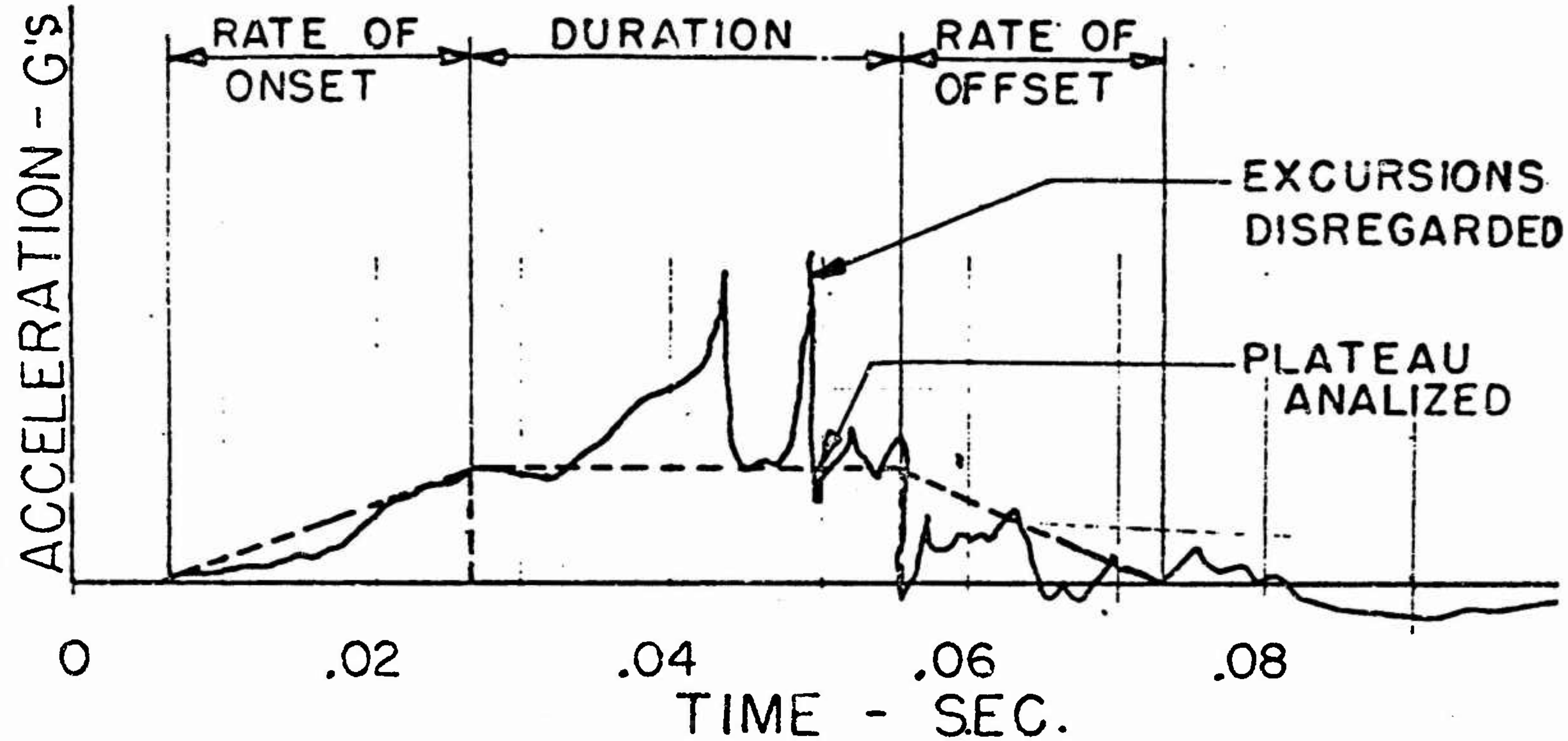


Figure 4

Excursions Less Than 10 Milliseconds Are Often Ignored [20]

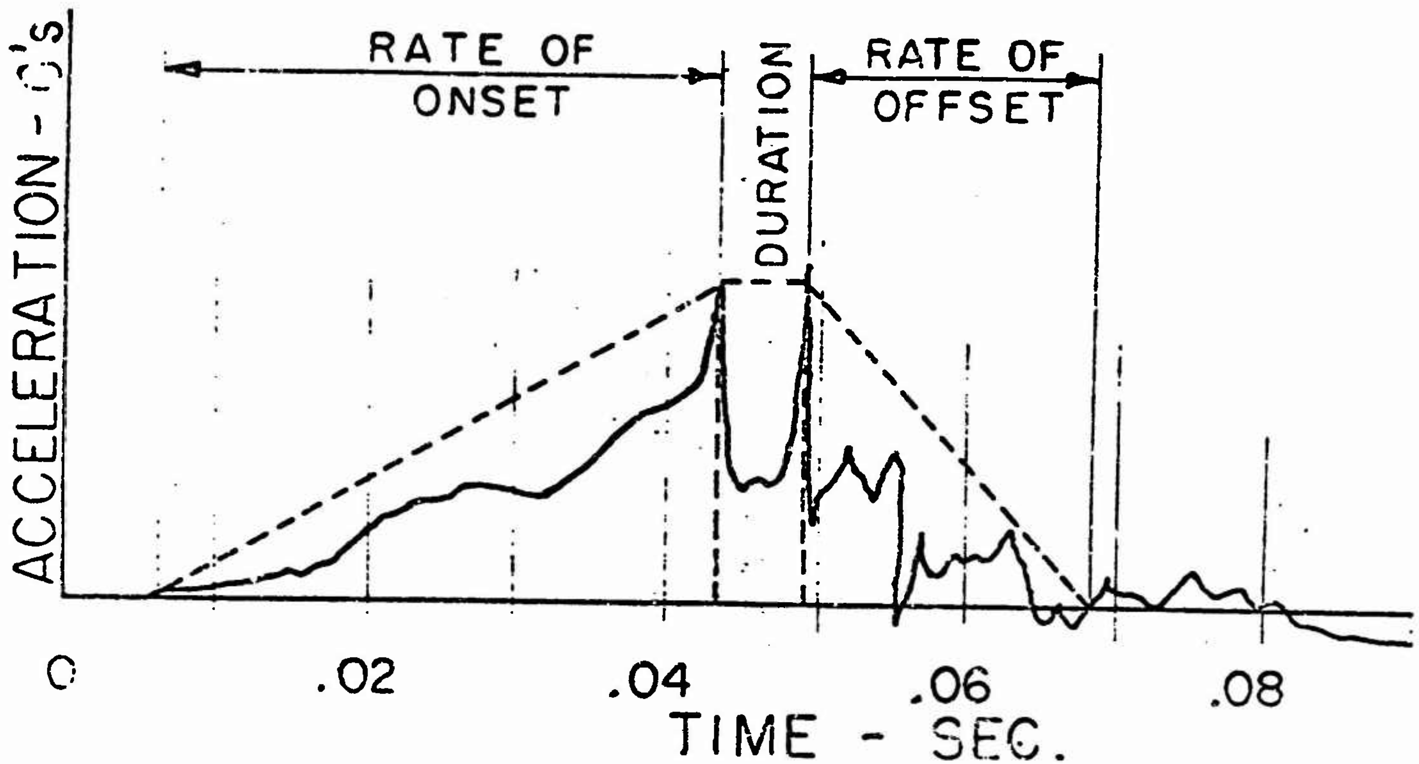


Figure 5

Rate of Onset Can Be Misleading [20]

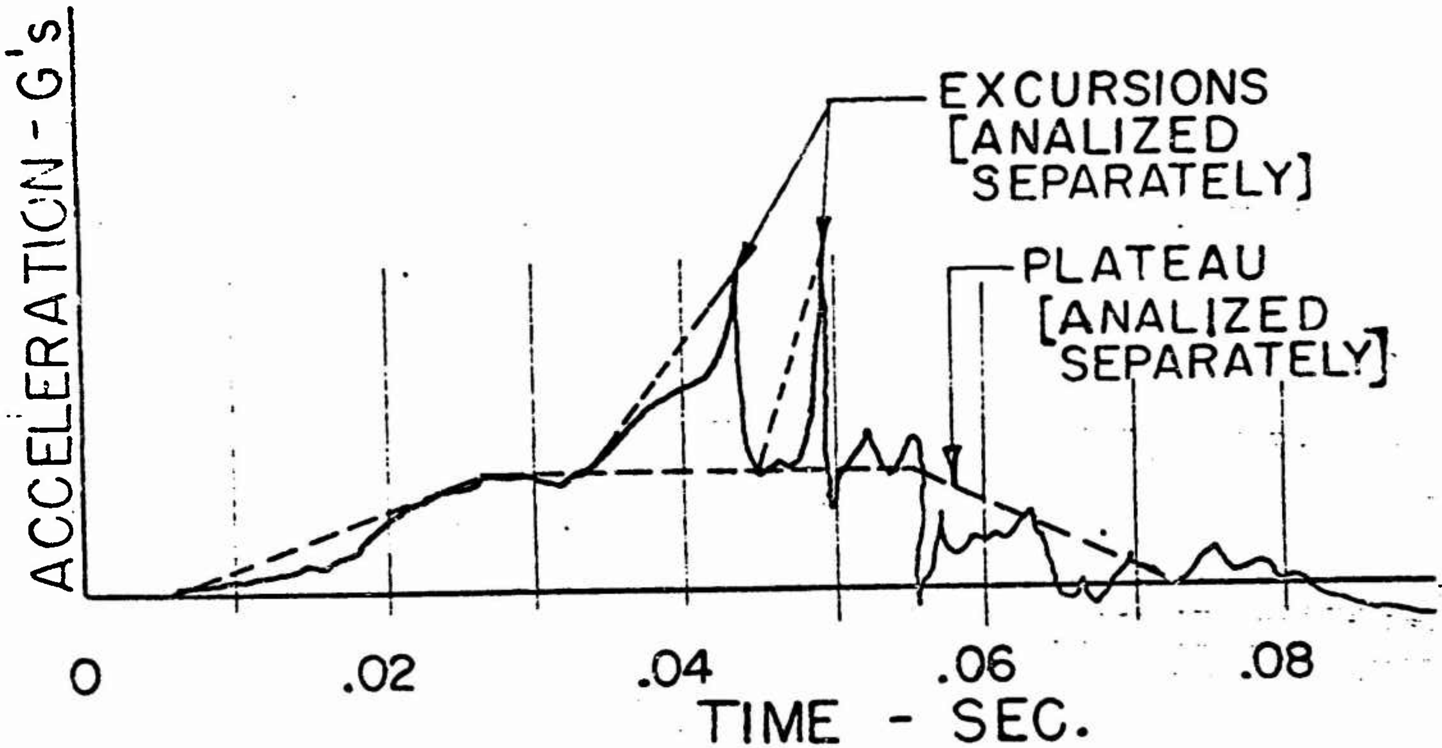


Figure 6

Treating the Plateau and Excursions Separately [20]

As in any new field of scientific research there is a need to coherently organize terms perculiar to acceleration investigations. We will use those terms which appear to be generally accepted by most researchers in this field. And most scientists agree that there are five factors which determine human body's tolerance to abrupt acceleration. These are magnitude, duration, rate of onset, direction, and body restraint [10:2], [17:1], [49:585], [39:734]. In subsequent chapters these terms will be introducted and defined. We will see that one factor cannot be separated from the rest but all are dependent one upon the other to define human tolerance.

Chapter 3

THRESHOLDS

Human body reactions to acceleration forces can be placed in three categories which I have classified by defining the categories' thresholds, or limits. Since we have defined humans as differing from one model to another necessarily nebulous classification boundaries define human reactions and injuries. These three levels, tolerable, injurious and fatal, are discussed in ascending order of impact force.

Eiband defined his use of tolerable in his often quoted report.

> Medically, a tolerable acceleration may be defined as one in which the subject is not debilitated or traumatically injured. Debilitation is a state of abnormal weakness, languor or feebleness. The effect does not necessarily result from wounds or lesions. Traumatic injury as defined for this report includes wounds and lesions but does not include superficial cuts and wounds, bruises, or strap abrasions, as such injuries would not deter a rational escape attempt. Either debilitation or traumatic injury then defines an exposure that exceeds the limits of voluntary tolerance. [10:2]

Use of tolerable by most authorities does not agree with Eiband's definition. Their use of tolerable limit implies levels of impact reached without incapacitation. In this range the human can sustain injuries but the injuries will not hinder escape from the environment. Injuries sustained are generally reversible.

I also disagree with Hegenwald who states acceleration within tolerance limits produce no worse than short periods of extreme discomfort on unconsciousness. The specific limits, he indicates, "include petechiae, pain, difficulty of respiration, blackout-to-unconsciousness, and threshold of shock and mechanical injury" [17:2].

In the injurious range moderate or severe trauma can seriously impair the subject's functional ability but the occupant may survive. He may be incapacited and not able to escape. The upper injurious limit coincides with the fatal limit.

At this point it is wise to emphasize that these limits are defined by trauma caused by impact and not secondary causations of impact. For example, a pilot may suffer only minor injuries as a result f a smooth wheels up landing yet a fire extinguisher breaks loose from its bracket and strikes the pilot's head causing a fatal concussion. The fire extinguisher, called a far flung missile, hit his head with forces in the fatal range. In this same wheels up landing the copilot's loose shoulder harness lets him fall forward upon impact with sufficient impetus to receive a crushing chest blow on the control wheel. This flailing, called a near flung missile, and the pilot's head strike are secondary results of aircraft impact and not within the purview of this paper. Investigation may reveal that forces causing injuries suffered by these two airmen as a direct result of impact were well within the tolerable range.

I.e., just considering the line of force from ground to the men through intervening aircraft structure there should have been little human damage in this abrupt acceleration.

Chapter 4

MAGNITUDE

Magnitude is another way of saying acceleration. Commonly the term used is G which is a ratio expressing acceleration. When multiplied by acceleration due to gravity (g), generally 32.2 ft/sec/sec, the result yields a definitive acceleration in distance per time squared. For example, an acceleration of 10G is 322 ft/sec^2 or it could be stated as 36.6 miles/min^2. Some literature states this acceleration as 10g; however, capital G is the acceptable use today. G also represents force. The 10G acceleration on a 200 pound man indicates a force of 200 pounds.

Thoughts of impact often brings to mind visions of a sudden stoppage, or at least decreased velocity. Such is true if we consider falling from heights or ramming an auto against a wall. This type impact is termed a deceleration or, scientifically, a negative acceleration. However, there are impacts that cause a positive acceleration, or increased velocity, such as an ejection seat or catapult. If an automobile standing at a traffic signal is rammed head on the acceleration, or positive acceleration if you wish, will

cause the driver to lean forward and perhaps hit the windshield. Likewise, if the automobile is moving, hits a wall head on, and thereby has a negative acceleration, the driver will again tend to hit the windshield. In both cases the inertial reaction of the vehicle's occupant is the same whether he experienced a positive or negative acceleration. Since the body's reaction to acceleration is essentially the same whether it is positive or negative, I will use acceleration to mean both unless the adjective is required for clarification.

While one might expect that tolerance is proportional to acceleration magnitude in a pulse, this may not necessarily be true. Consider the pulses in Figure 7.

Will the human react more to X than Y? The answer depends on many factors and may never be known except by experimentation. Since magnitude X is twice Y and base duration of Y is twice X, the velocity change, which is the area under the traces, for both pulses is the same. And, in fact, velocity change, while not one of our five stated parameters, is often used in recent literature as a significant factor. Magnitude does <u>not</u> define tolerance. Nor does acceleration cause injury. We will see that stress, a result of acceleration, causes injuries [19]. However, any cogent discussion of magnitude and human tolerance is fraught with danger without appreciating the role of duration which is discussed next.

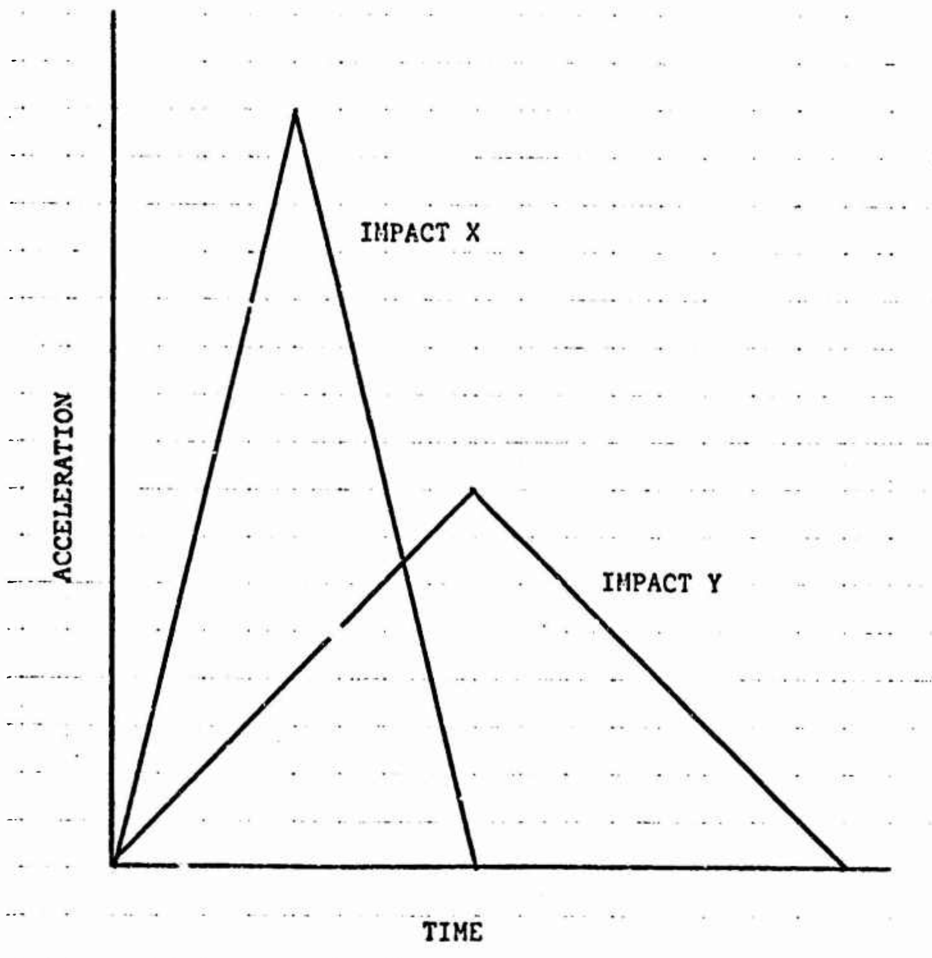


Figure 7
Two Hypothetical Traces

Chapter 5

DURATION

Duration terminology associated with accelerations is ill defined in the literature. While it appears that duration delineation actually is a function of individual human reaction and not a definite time interval, efforts have been made to give readers a feel for impact durations. Snyder [37:2] states that abrupt accelerations commonly refer to impacts less than .02 seconds while Gauer [11:15] indicates 0-2 seconds is a logical period. AGARD, while admitting there are prolonged accelerations and impact decelerations, states only that the former lasts at least several seconds [13:11]. Meeham refers to accelerations more than one second as slow and less than one second as rapid[34:6] while Roth says "Impact . . . involves time intervals which may be stated approximately as ranging from 1 second downward . . ." [15:50]. Ruff uses individual reaction.

> In aviation medicine, the border line between prolonged and brief acceleration has been drawn at that point where, however much the acceleration be increased, there is not direct effect on circulation and respiration.[48:584]

Actually there is an indefinite zone between abrupt and prolonged acceleration in which the effects of both can

occur simultaneously. In any case, since most crash pulses have base durations of about 0.02 seconds to 0.2 seconds, we are interested in human design limits in abrupt accelerations [7:127], [26:24].

Where this time is measured on a pulse is sometimes difficult to determine from test documentation. For example, the base times of Figures 4 and 5 are essentially the same whereas the peak or plateau times are quite different, in Figure 5 approaching zero. Actually the scientist is interested in both times.

How does acceleration duration affect human tissue response? It appears that in impacts less than 0.2 seconds tissues are essentially rigid and inelastic to forces. There will be failure by exceeding physical characteristics of tensile, compressive, or shear strength. There is structural damage or failure. It is not uncommon to find torn aortas and other visceral attachments on high-energy impacts before reaching their normal elastic limit [38:283].

From 0.2 to 3 seconds duration, there are reactions due to hydraulic displacement of fluids such as rupturing of blood vessels and pressure damage to cell membranes. Hence, hydraulic failure. 0.2 seconds is the latent period to overcome viscosity of fluids and elasticity of tissues [39:738].

Most airmen are familiar with the functional disorders created by accelerations longer than 3 seconds. Commonly associated with the human centrifuge and aircraft

maneuvers, these forces prevent flow of oxygen carrying blood and thus produce secondary central nervous system hypoxia. Some investigators speculate that accelerations less than 0.006 seconds react in a completely different manner. For example, why don't karate experts sustain fractured hands [37:18]?

Throughout subsequent discussions of abrupt acceleration we will discover that, as the duration decreases, the tolerance magnitude will tend to increase.

Chapter 6

RATE OF ONSET

Rate of change of velocity is another way of expressing acceleration. Rate of onset, rate of application, jolt, and jerk all refer to the rate of change of acceleration. Determination of velocity change from the acceleration trace was discussed in Chapter 4. Just as the slope of a velocity-time trace furnishes acceleration, so the slope, or tangent, of an acceleration-time pulse will yield rates of change of acceleration.

The steeper slope of impact X in Figure 7 indicates a higher rate of onset when compared to impact Y. However, since the slope of a typical curvilinear acceleration pulse is constantly changing it is difficult to determine at what time intervals rate of onset should be computed. Often two points on the trace are used as in Figures 4 and 5 so that rate of onset is actually a mean rate to reach some magnitude, generally the maximum. Note that in Figure 6 three different slopes are measured.

If a scientist computes rate of onset to a certain magnitude assuming a linear acceleration, some authorities believe rise time, i.e., the time to reach that magnitude, is more descriptive than rate of onset. This argument has

merit since rate of onset implies using one parameter, magnitude, to define another, rate of onset, which is poor scientific procedure.

When an acceleration decreases the negative slope is referred to as rate of offset or rate of decay.

While there has been much research by varying magnitude and duration the effects of rate of onset have not been examined separately and, therefore, knowledge of the effects of rate of onset is scant. Generally, the lower rate of onset is more tolerable for the same duration. Also tolerable magnitude decreases as the rate of onset increases [10]. The higher the rate of application the more severe the effect. Stresses are a function of the rate of application of force, and since acceleration is a function of force (F=ma) then rate of onset determines the stresses subjected by the human body [49:5-21].

As the rate of onset increases, particularly below 0.15 second rise time [14], the phenomenon called overshoot is encountered and the rate of onset tends to be the parameter that defines human tolerance. Overshoot is caused by the occupant not keeping pace with his environment and can be compared to rapidly stepping on a bathroom scale. Easing onto the scale will prevent oscillations, or overshoot of the scale mechanism.

A pilot ejected upward from his aircraft may enter overshoot if he does not accelerate at the same rate as his seat. For example, the occupant may accelerate less rapidly,

i.e., a lower rate of onset, most likely caused by compression of his seat cushion after firing the ejection mechanism. As the cushion compresses it increases its resistance to compress.

If the cushion can compress no further, the occupant has "bottomed out." The seat wallops the occupant to accelerate him more rapidly, that is, a higher rate of onset, in order that he can attain the same velocity as the ejection seat. As the pilot accelerates faster than his seat he enters overshoot. Moral: use hard cushions on ejection seats.

If overshoot occurs in the body's internal organs then damage can result. The body cage may accelerate but viscera, not being rigidly attached to the skelatel framework, will begin moving with the body when attaching tissues are stretched a great deal. In reality there are built in dampers or shock absorbers which modifies these effects of overshoot [31:9].

Chapter 7

DIRECTION

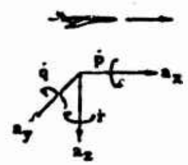
Accelerative force is a force which is exerted in the acceleration of an object. It is in the direction of movement of the object. If an aircraft is accelerating forward straight and level, its accelerative force is said to be forward. Inertial force or inertial resistance is equal but opposite to the accelerative force. An aircraft accelerating down a runway has the vector of the accelerative force pointing forward and the vector of the inertial force pointing aft. Inertia is further explained by Newton's First Law of Montion called Law of Inertia. "A body at rest tends to remain at rest and a body in motion tends to remain moving at the same speed in the same direction."

Biomedical researchers, pilots, and design engineers have used different reference systems when discussing accelerations. In an effort to organize this terminology NATO's Advisory Group for Aerospace Research & Development (AGARD) devised Table 1. Subsequent revision by AGARD [13] expands on this table but tends to be confusing for this paper's requirements.

Work in prolonged acceleration has demonstrated the role of retinal circulation to determine physiclogical end points of acceleration experiments. Since inertia of

Table 1

Acceleration Direction Equivalents [12]



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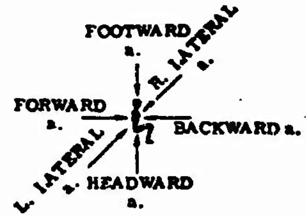
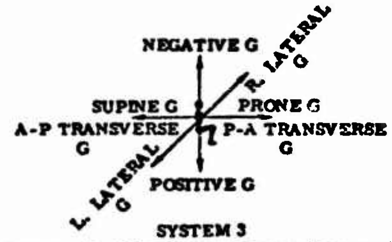
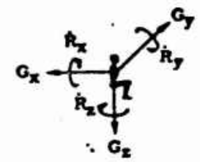


SYSTEM 2



SYSTEM 3



SYSTEM 4

LINEAR MOTION	TABLE A Direction of Acceleration		TABLE B Inertial Resultant of Body Acceleration		
	Aircraft Computer Standard (Sys. 1)	Acceleration Descriptive (Sys. 2)	Physiological Descriptive (Sys. 3)	Physiological Computer Standard (Sys. 4)	Vernacular Descriptive
Forward	$+a_x$	Forward accel.	(1,2) Transverse A-P G Supine G Chest to Back G	$+G_x$	Eye Balls In
Backward	$-a_x$	Backward accel.	Transverse P-A G Prone G Back to Chest G	$-G_x$	Eye Balls Out
Upward	$-a_z$	Headward accel.	Positive G	$+G_z$	Eye Balls Down
Downward	$+a_z$	Footward accel.	Negative G	$-G_z$	Eye Balls Up
To Right	$+a_y$	R. Lateral accel.	Left Lateral G	$+G_y$	Eye Balls Left
To Left	$-a_y$	L. Lateral accel.	Right Lateral G	$-G_y$	Eye Balls Right
ANGULAR MOTION					
Roll Right	$+\dot{p}$		Roll	$-\dot{R}_x$	
Roll Left	$-\dot{p}$			$+\dot{R}_x$	
Pitch Up	$+\dot{q}$		Pitch	$-\dot{R}_y$	
Pitch Down	$-\dot{q}$			$+\dot{R}_y$	
Yaw Right	$+\dot{r}$		Yaw	$+\dot{R}_z$	
Yaw Left	$-\dot{r}$			$-\dot{R}_z$	

FOOTNOTES:

1. Large letter, G, used as unit to express inertial resultant to whole body acceleration in multiples of the magnitude of the acceleration of gravity. Acceleration of gravity, g_o, = 980.665 cm/sec^2 or 32.1739 ft/sec^2
2. A-P, P-A refers to Anterior-Posterior, Posterior-Anterior.

the human body's organs actually cause physiological effects during acceleration, I will use physiological acceleration terms which refer to the inertial movement of the eyes, an organ, to describe direction.

If a forward moving vehicle strikes an object which retards movement, the driver, following Newton's First Law, tends to keep moving until he is stopped by restraints or his vehicle's interior. This tendency to move forward is called eye balls out since the eye balls will tend to keep moving forward. A comparable analogy can likewise be used to describe eye balls in when a standing vehicle is struck from behind or the driver accelerates the vehicle. Eye balls down result from an ejection seat upward and, eye balls left results if struck on the left door of the car. Explanation of eye balls down and right follow from the above examples.

Do not confuse positive or negative G in Table 1 with positive or negative acceleration discussed in Chapter 4.

Chapter 8

RESTRAINT

Of the five factors which affect human tolerance body restraint is the most controllable by the design engineer. Body restraint refers not only to restraining by harnessing but also includes body supporting techniques. In either case the greater the area over which a load is applied the smaller the load, or force, per unit area, and less probability of injury. As the area of support becomes smaller the pressure increases.

Since the human skeleton is the strongest body structure and is rigid the best way to distribute impact loads is over the skeletal framework of the body rather than subjecting soft structure to extensive pressure. Hence, lap belts should support the pelvic bones.

By restraining the human over his body girdles, especially the shoulders and pelvis, he will experience minimum elastic response and thereby avoid dynamic overshoot. This will allow the occupant to decelerate with his environment. In the sitting position forces should be transmitted directly to the pelvic structure and not via the vertebral column [10:1]. Shoulder harness should prevent jackknifing of the vertebral column and sustaining wedge

shaped compression fractures.

Physical fitness helps to strengthen the muscles protecting viscera. However, awareness of an imminent impact triggers musculature contractions which furnishes some internal body restraint for normal tissue tonicity.

Individually fitted contoured plastic couches selected as body support for project Mercury combine most of the principles for protection against eye balls in (spineward) acceleration.

Testing has shown that seat to floor attachments often lack sufficient strength to sustain human tolerance loads. This failure in the route of energy from vehicle to occupant support before human tolerance is reached endangers the occupant by flying him about his environment. Knowing human impact tolerance parameters the engineer can design strength requirements for structure, seats, and belts restraining and supporting an occupant.

It should be obvious that chances of survival are higher if the restraint system is designed for loads higher than human tolerance.

Chapter 9

IMPACT INJURY

Earlier I emphasized that stress and not rapid acceleration magnitude causes injury in the human non-rigid b[illegible]. The following explaination clearly states why.

> Any internal fracture or rupture occuring in the body is caused by the local stress that has momentarily exceeded the maximum which the material in question can support. Because stress in the torso is very difficult to measure, while acceleration is comparatively simple, there exists a strong tendency to correlate injuries sustained in flight with the magnitude of the acceleration to which the injured person was subjected. Because stress is actually the cause of injury, this approach tacitly assumes that stress is proportional to acceleration, which is strictly true only for a rigid body. For non-rigid bodies, stress is related to acceleration in a more complicated way and may, for example, depend not only on the instantaneous value of the acceleration, but on its entire time history. Thus, in motions for which the human body is not approximately rigid, the use of the maximum value of the acceleration as a tolerance criterion may be invalid. Two motions that have the same values of maximum acceleration may have quite different values of maximum stress, and thus it is possible that one such motion results in injury while the other does not. [19]

In the discussion of duration we found that impact injuries are due to mechanical failures in the body. Forces of inertia developed on impact propagate into the body and appear as tension which tends to change the relative position of neighboring tissue elements. Because of various elastic systems involved when considering internal organs, dynamic

response of various organs to accelerative forces may take intricate forms. This may cause differential accelerations of various viscera which in turn may lead to injurious stresses on organs and connective tissues. Crash testing gives evidence of repetitive pulses occurring near the natural frequency of parts of the human body. Even with low magnitudes body members can be stimulated at resonant frequencies thereby causing development of forces which greatly exceed the original force. Since each organ has its own natural frequency, there will be different reactions in each organ. Moreover, if a tissue mass is set in periodic motion at its resonant rate, internal or supportive structures can be ruptured at less than nonresonant energies. The total effect can be rather severe [23], [26].

With its curved architecture and spongy interverte-bral disc the human spine is hardly an ideal structure to absorb thrusts along its long axis without suffering insults in the bargain. Also, because of the body's anatomical structure, accelerations of larger magnitude can be sustained when the accelerating force is imposed perpendicular rather than parallel to the long axis of the spine. In this mode the body's organs have less distance to displace and hence less chance of tearing or rupturing vital organs.

Ruff [47] and Henzel [18] agree that the weak point

in the vertebral column is the 12th thoracic[1] (T12) vertebra which carries approximately 50% of the total body weight. Figure 8 summarizes 1958-1963 incidences of spinal fractures from the 18-21 G Martin-Baker seat [18:27]. Many of the injuries sustained in ejection are compression fractures of vertebrae and almost all are wedge compressions involving the anterior vertebra lips. Downward momentum causes bending moments on the spine which flexes anteriorly unless adequately restrained.

Nor is vertebral fracture induced in only the longitudinal direction. Meehan states that in rapidly applied accelerations ". . . dynamic loading of the spinal column and of the larger, heavier vircera pose the major problem" [34:9]. Beeding reports that many of his subjects developed back pains in the 3rd lumbar (L3) to the coccyx which was tender to palpation for approximately three weeks after transverse accelerations [3].

von Gierke cogently summarizes impact injury.

> The wide latitude of possible physical action of impact energy and the short time of its duration make it very hard to analyze its physiological effects, short of mechanical injury. For acceleration forces parallel to the spine, compression of the spinal column limits voluntary tolerance. Persistent neuralgic and sciatica-like pains resulted from such exposures. For forces transverse to the longitudinal axis for which tolerance limits are higher, systems of various degrees of shock were the first limiting voluntary tolerance, as Stapp

---

[1]The human's 24 ribs articulate with 12 thoracic vertebrae. See Figure 9.

observed in his large series of pioneering experiments. Subjects turned pale, perspired, and exhibited transient rises in blood pressure. In one case, brief attacks of low blood pressure and albumin in the urine for about six hours after the run were observed. More severe loads resulted in unconsciousness. At the maximum acceleration load applied, immediate effects were sometimes not pronounced, but delayed effects occurred with gradual onset over the next 24 hours. Human tolerance to lateral impact has not yet been studied up to critical levels, although recent tests established tolerability of certain velocity changes (up to 19 ft./sec.) and peak accelerations (up to 22 G) for a specific protection system (maximum lateral support). [34:48]

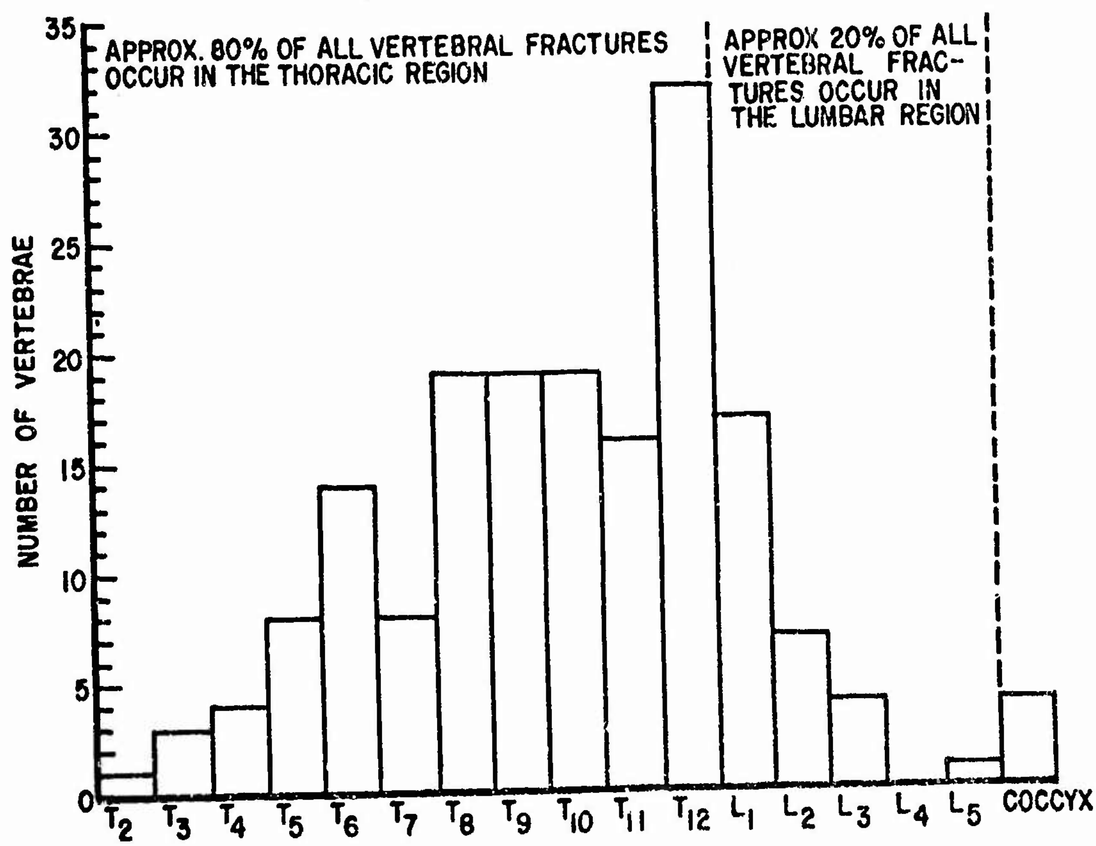


Figure 8

Incidence of Vertebral Injury In
Aircrew Surviving Ejection [18]

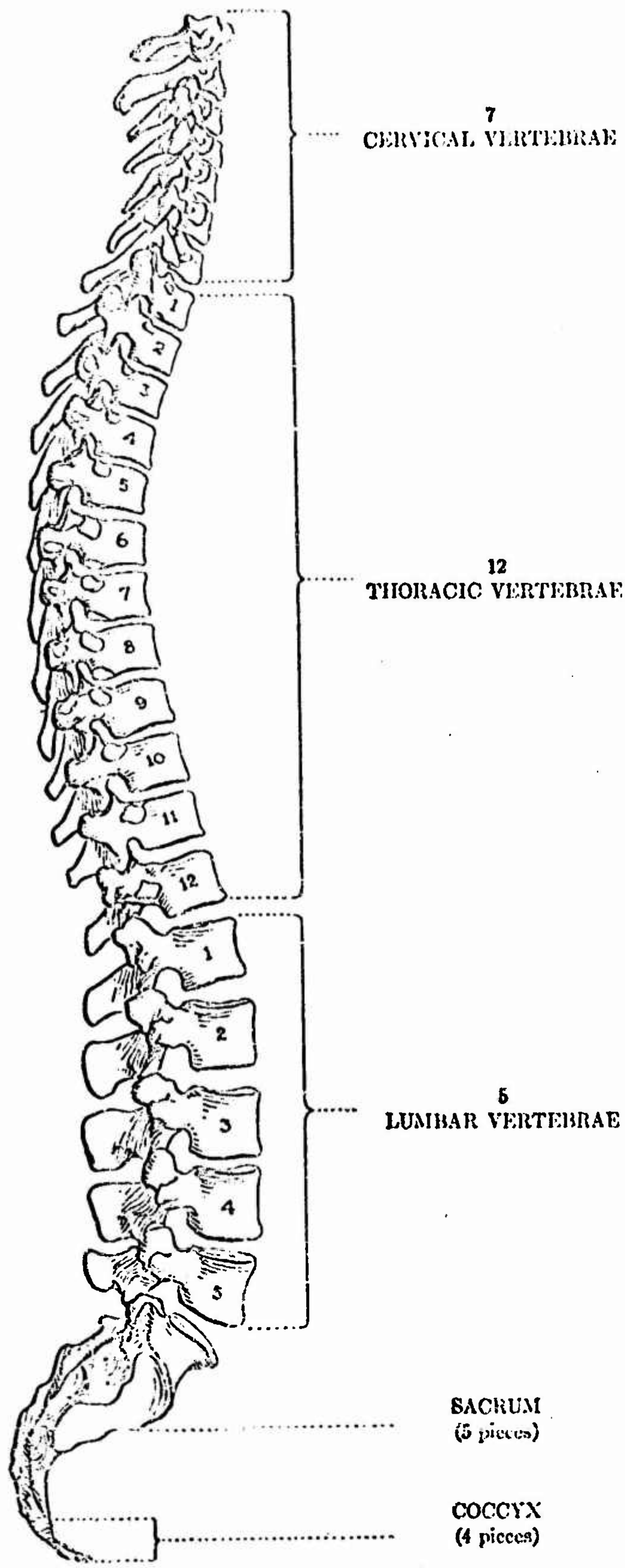


Figure 9

The Human Vertebral Column

Chapter 10

TOLERANCE LIMITS

At this point the reader may be under the impression that defining human tolerance levels is difficult, which is true, and any values given may not be valid for all individuals, which is also correct. Though nebulous tolerance limits may lead to hesitant acceptance of this research, the fact remains that any parametric values which are documented would prove useful to those confronted with the task of designing for crash survival. Even the most recent literature admits that tolerance limits of man are known approximately, but only under certain conditions of support and restraint [32:1].

The remainder of this chapter furnishes some accepted values of human acceleration tolerance based on inertial direction of acceleration. We will assume that the human is well restrained and is seated.

Eiband's summary of human tolerance to rapid accelerations is often quoted in literature. His charts are used to supplement written data in this chapter.

Eye Balls Out

The Air Force Flight Surgeon's Manual furnishes tolerance limits with respect to the three remaining parameters of rate of onset, magnitude, and duration.

1. Limit of tolerance for rate of change of deceleration: 1500 G per second at 40 G for 0.16 seconds duration or less.
2. Limit of tolerance for magnitude of force: 50 G attained at 500 G per second rate of onset and duration of 0.20 seconds or less.
3. Limit of tolerance for duration of forces: 25 G or more, at 500 G per second rate of onset, for one second. [49:5-28]

The above values are taken from Stapp's experiments [38:286]. The Flight Surgeon's Manual does not define the use of tolerance; however, if one accepts the definition in this paper the values above are the very limits of tolerance and, for some individuals, are certainly within the injurious environment.

For example, the subject in item 3 above was debilitated but conscious. Although the subject could stand erect momentarily, and could control hand and arm movements following release of the straps, he could neither see nor maintain a standing posture. The subject returned to normal duty in five days [10:7].

Figure 10 summarizes the literature on sternumward acceleration with respect to magnitude and time. Figure 11 demonstrates that even with a large acceleration magnitude a lower rate of onset is generally more tolerable.

Beeding's work on 14 human sled runs is summarized in Table 2. Summated G refers to the square root of the sum of the squared X, Y, and Z axis.

Table 2

Summary of Fourteen Runs
(Eye Balls Out) [2]

Number of Runs	Summated Subject Peak (G)	Ave. Onset Time (seconds) Sled	Ave. Onset Time (seconds) Subject	Symptoms
7	30.3-34.8	0.024	0.034	Burning rectum Sore coccyx 1-5 days Stiff neck 1-3 days
6	35.3-38.4	0.023	0.032	Albuminuria 1-2+ clear in 24 hours Faint blood pressure 94/48 Blurred vision in left eye Opthalmoscopic negative
1	39.8	-	-	Age: 22, weight: 175, Height: 6'3" Syncope-blood pressure 78/? EKG nodal rythm post-impact Anterior compression fracture of T5 and T6 Linear fracture of anterior superior border of L5

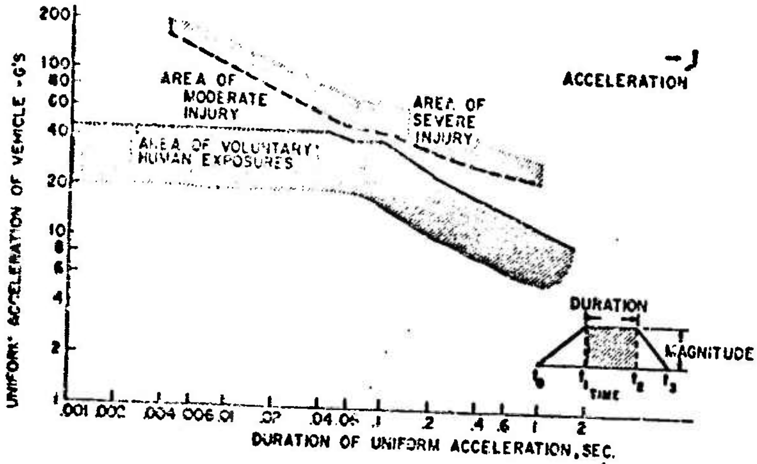


Figure 10

Magnitude Tolerance to Eye Balls Out Acceleration [10], [14]

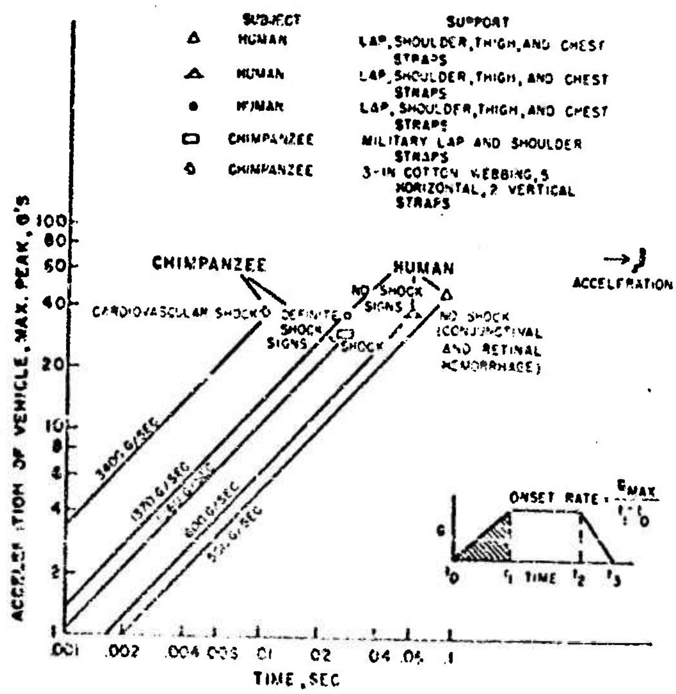


Figure 11

Rate of Onset Tolerance to Eye Balls Out Acceleration [10], [14]

Eye Balls In

Generally associated with rearward seating in aircraft we might expect tolerance in this position to be higher because there is more contact, and hence better restraint, between the supporting structure and body. Beeding suggests that limits with 0.04 second base duration may be in the area of 83 G at 3800 G/second [6:10]. This peak chest 83 G run had a sled input of 40 G and 2100 G/second which once again demonstrates overshoot with high rate of onset. After the run Beeding, the subject, gradualy went into shock but recovered in ten minutes. He was hospitalized for three days. Beeding returned to duty five days post-run with no apparent lasting effects.

Two runs Beeding comments upon are closer to Eiband's expected injurious limits.

Table 3

Summary of Two Runs (Eye Balls In) [6]

Magnitude (G) Sled	Magnitude (G) Chest	Base Duration (Seconds)	Rate of Onset (G/Seconds) Sled	Rate of Onset (G/Seconds) Chest	Age	Weight	Height
37.5	52.6	0.044	1517	2156	27	118	5'5"
35.4	67.0	0.042	1351	2594	34	192	6'

Symptoms for both subjects were: (1) dyspnea for four minutes post-run and (2) back pain from L3 to coccyx initially along line of spine, gradually shifting to points bilateral to L3 and persisting for six weeks post-run.

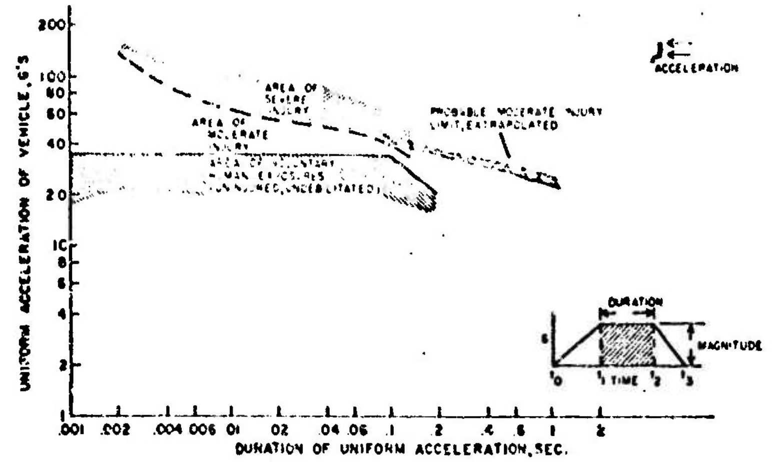


Figure 12

Magnitude Tolerance to Eye Balls
In Acceleration [10], [14]

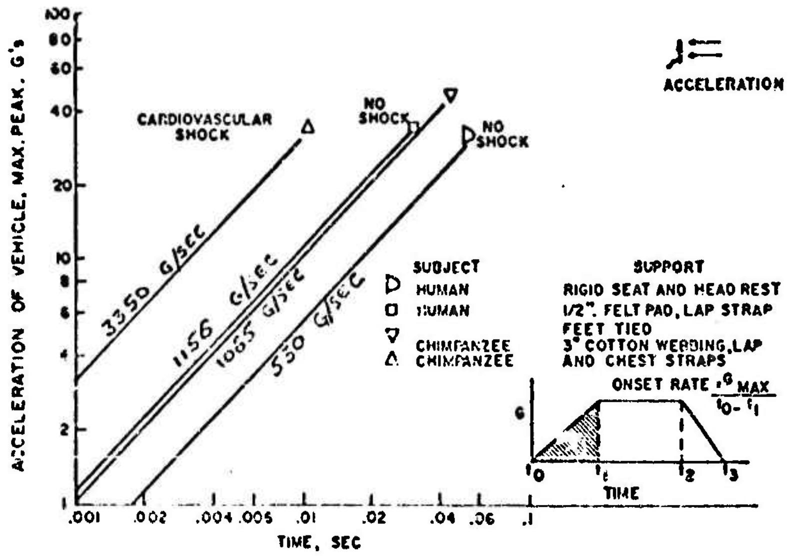


Figure 13

Rate of Onset Tolerance to Eye
Balls In Acceleration [10], [14]

Eye Balls Down

The advent of jets in the early 1940's required means to escape from these high speed aircraft. German research determined strength of the spinal column in impact accelerations [48:590]. Subsequent investigations verified that the vertebral column is very susceptible to injury in the longitudinal direction, probably due to poor body positioning during ejection. In the chapter on impact injury von Gierke emphasizes that the spinal column limits tolerance in this direction. Tolerance is lower when forces are applied parallel than when applied perpendicular to the spine.

The Flight Surgeon's Manual states that "maximum tolerance limits for upward ejection have been estimated at 33 G's with a rate of onset of 500 G's per second, provided an ideal position is assumed." Latham suggests tolerance in 300 G/second with a peak acceleration of 25 G's [23]. The M-5, standard ejection seat for USAF fighter aircraft, accelerates for about 16 G's for 0.2 seconds. Velocity change is 60 ft/second [49:5-22].

Eye Balls Up

Information is this direction is scarce. However, estimated values are thought to be conservative and less than eye balls down. The Air Force indicates limits for downward ejection as 16 G with a rate of onset of 200 G/second [49:5-22].

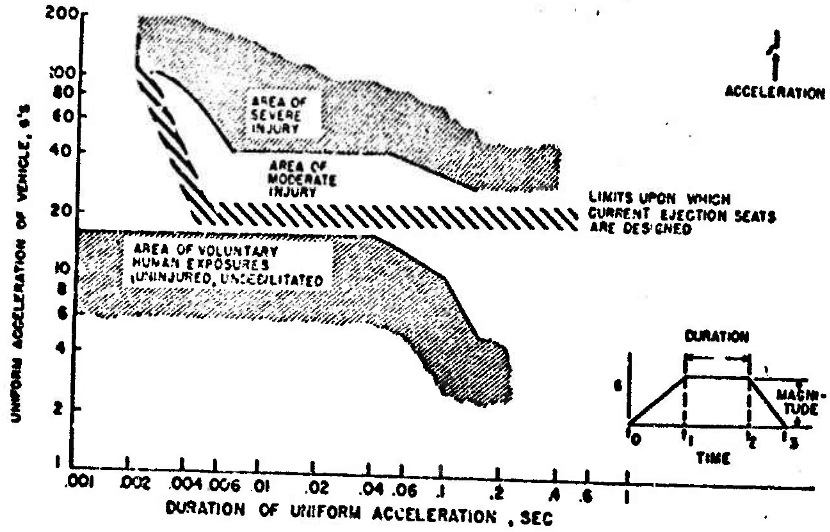


Figure 14

Magnitude Tolerance to Eye Balls Down Acceleration [10], [14]

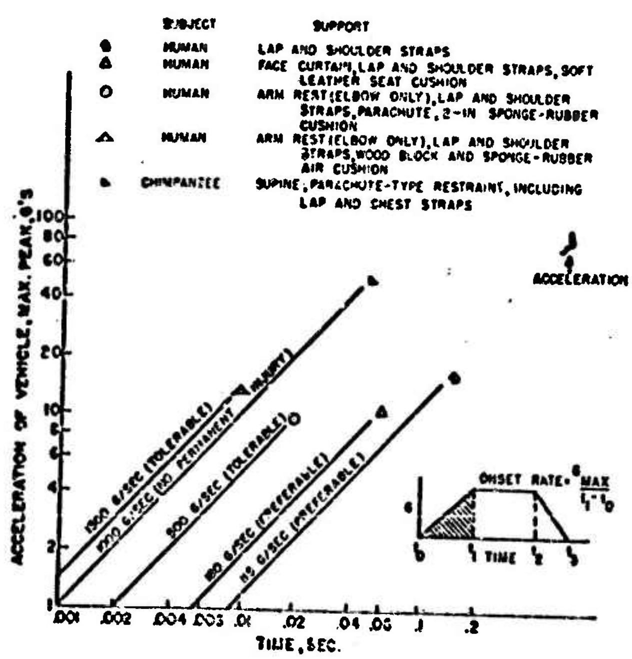


Figure 15

Rate of Onset Tolerance to Eye Balls Down Acceleration [10], [14]

Adequate restraint must be kept in mind. As always the object is to transmit accelerative forces direct to the pelvis. If shoulder straps are used with a loose lap belt in this direction then overshoot imposes compressive loads on the spine with possible damage [11:181].

Eye Balls Left/Right

Of the three major body axes least research has been in the lateral G_y direction. Limits are vague and realistic human tolerance data is at best a conjecture.

Testing 52 subjects Zaborowski found no reported physiological changes after exposures to inputs of 11.59 G's average and duration of approximately 0.1 seconds using lap belts and shoulder harness [8:108]. He stopped at this point because other data had indicated that sustained relative bradycardia might result.

Weis et al. indicated that, with maximum lateral support, tolerance is at least 20 G, onset rate about 1,000 G's/second, with base duration of 0.065 seconds [54].

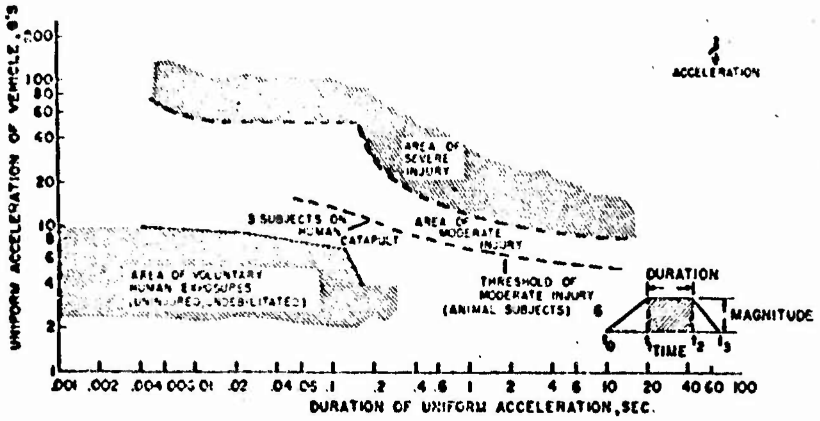


Figure 16

Magnitude Tolerance to Eye Balls
Up Acceleration [10], [14]

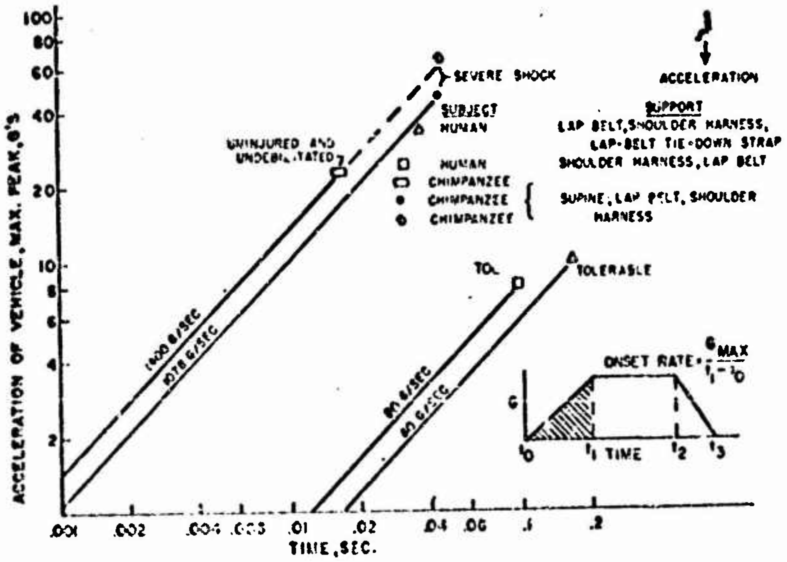


Figure 17

Rate of Onset Tolerance to Eye
Balls Up Acceleration [10], [14]

Chapter 11

SUMMARY AND FUTURE STUDY

Caution must be used in applying data presented in the preceeding chapter. In this testing the supports were well designed with minimum slack of the harnesses while young healthy volunteers were expecting impact exposure. This is certainly not tolerance criteria anticipated in an average airline passenger.

One conclusion can be made. With proper restraint the human can survive impact accelerations of great magnitudes. Adequate support of the vertebral column will assist in preventing vertebral fractures, the single most frequent cause of major non-fatal injuries. Limits in Figure 18 show that thresholds are higher when forces are applied perpendicular than when applied parallel to the spine.

This paper assumed a one pulse impact. Little work has been done on the effects or repetitive impacts nor, rarely, have force vectors other than the three major axes been considered. Investigators are forgiven from shying from the extreme complexity of rotary loads in rotational fields and tumbling in cartwheeling accidents. However, there is still much to be investigated and learned.

Expressing human tolerance to abrupt accelerations with numerical values leads one to the precipice of disaster unless one realizes that five major parameters are involved. Even establishing direction and restraint leaves a three dimensional matrix which itself is subject to modification when defining different humans. In this connection it is appropriate to recall a statement made by Lord Kelvin in 1889. "I often say that when you can measure what you are speaking about and express it in numbers, you know something about it. But when you cannot measure it, when you cannot express it in numbers your knowledge is a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarely advanced to the stage of science, whatever the matter may be."

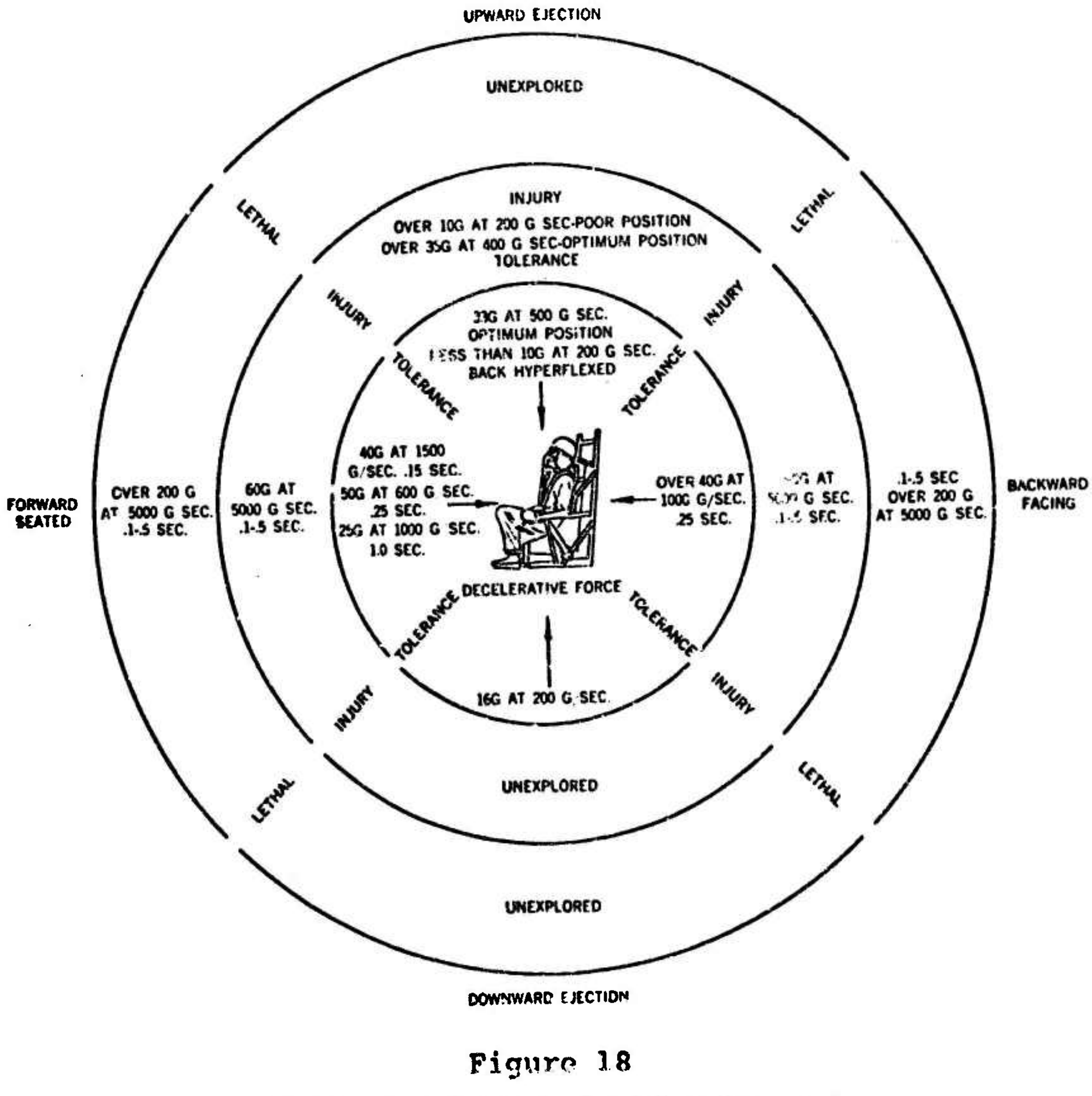


Figure 18

Limits for Forces Applied Through Transverse and Longitudinal Axes [49]

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APPENDIXES

Appendix A

A Few Results of Acceleration Research [43], [53]

TYPE OF G	DIRECTION OF BODY MOVEMENT	AIRCRAFT MANEUVER	EXPERIMENTAL HUMAN EXPOSURES (MAXIMUM)	PHYSIOLOGICAL LIMITS HUMAN	ACTIVITIES	AMAL CENTRIFUGE ANIMAL EXPOSURES	ANIMAL PATHOLOGY
POSITIVE (Eyeballs Down)	Head to Foot	Pull Out or Tight Turn	8 G for 15 Sec.	Blackout to Unconsciousness	All Centrifuges	40 G for 15 Sec. Chimpanzee	Slight Damage with Venous Congestion, Intravascular Thrombosis, and Leg Muscle Hemorrhage
			4.5 G for 5 Min. with G Suit	Pain in Legs and Blackout			
		Controlled Escape Deceleration	15 G for 1.75 Sec.	Unconsciousness	AMAL Centrifuge	15 G for 60 Sec. Chimpanzee	Unconscious at 9 G on Build-Up and Unconscious Then Confused After Run
		Ejection Escape (Upward)	20 G for 0.1 Sec. with Face Curtain - Arm Rest	Skeletal Damage (Spine)	AMEL and WADC Ejection Tower	40 G for 30 Sec. Monkey	Slight Damage
NEGATIVE (Eyeballs Up)	Foot to Head	Push Over	4.5 G for 5 Sec.	Subjective Pain	Rod Jocelyn	40 G for 30 Sec. Monkey	Intracranial Damage Subcutaneous Hematomas About the Head
			3 G for 32 Sec. with Special Helmet	Fullness of Neck and Head Bradycardia	WADC Centrifuge		
		Ejection Escape (Downward)	10 G for 0.1 Sec. with Leg Support	Pain	WADC Ejection Tower	40 G for 15 Sec. Chimpanzee	Severe Damage with Hematomas in Periorbital Tissues, Tongue, and Thyroid Gland: Venous Congestion and Intravascular Thrombosis with Intracranial Damage
TRANSVERSE SUPINE (Eyeballs In)	Chest to Back	Catapult Launching	5 G for 2 Sec.	No Damage	Carrier Takeoffs and AMAL Centrifuge	40G for 60 Sec. Chimpanzee	Slight Damage With Small Tear in Right Tympanum, Dulling of Patella - Re-flexes. Bruising Intern-ally Along Vertebral Column and Some Clotting Along Bronchial Blood Vessels. No Petechiae or Hemorrhages.
		Escape Deceleration or Higher Launching Stress	3 G for 9 Min. 31 Sec. Lying Flat	Monotony and Giddiness	WADC Centrifuge		
			15 G for 5 Sec.	Surface Petechial Hemorrhage and Pain in Chest	AMAL Centrifuge		
		Crash (Facing Aft)	55 G for 0.01 Sec. 35 G for 0.12 Sec.	Skeletal Damage	WADC Deceleration Track (Col. Stapp)		
TRANSVERSE PRONE (Eyeballs Out)	Back to Chest	Arrested Landing	5 G for 2 Sec.	No Damage	Carrier Landings and AMAL Centrifuge	40 G for 15 Sec. Chimpanzee	No Damage
		Escape Deceleration or Higher Landing Stress	15 G for 5 Sec. Special Chest and Leg Support	Surface Petechial Hemorrhage and Pain in Chest	AMAL Centrifuge		
		Crash (Facing Forward)	60 G for 0.01 Sec. with Special Harness 38 G for 0.12 Sec. with Special Harness	Skeletal Damage	WADC Deceleration Track (Col. Stapp)		
FLUCTUATING POSITIVE	Alternating Positive and Transverse	Uncontrolled Aircraft "Jostle"	1.5 to 6.5 G for 20 Sec. Combined with 72° Pitch and Roll	Additional Support Required Other Than Conventional Lap Belt and Shoulder Harness	AMAL Centrifuge	No Animal Exposures. This Type was Investigated to Determine Pilot's Ability to Actuate Controls	
CYCLIC	Alternating Positive Transverse Prone Negative Transverse Supine	Uncontrolled Escape Device "Tumbling"	No Human Experimentation Due to Severe Damage in Animal Exposures		AMAL Centrifuge	15 G and 20 rpm Chimpanzee	Fatal: Cerebral Hemorrhage - 3 Min. Exp. Severe Damage with Hematoma and Hemorrhage - 15 Sec. Exposure.
						35 G and 10 to 110 rpm for 10 Sec. Monkey	Fatal: Severe Damage with Hemorrhage in Lungs, Spleen, and Other Organs: Necrosis of Liver Cells, and Intravascular Clotting in All Organs. Increasing Damage with Increase in rpm.

NOTE: G Refers to the force on the body in multiples of the body weight. Wearing G-Suit Increases Human Tolerance to Blackout and Fatigue. The types of G, Transverse-Lateral and Fluctuating Negative have not been studied and are not included in this Chart. Rod Jocelyn - Stunt Pilot contracted by AMAL for negative G maneuvers.

AMAL - Aviation Medical Acceleration Laboratory, Johnsville, Pennsylvania
AMEL - Aviation Medical Equipment Laboratory, Philadelphia, Pennsylvania
WADC - Wright Air Development Center, Dayton, Ohio

APPENDIX B

Some Short Duration Accelerations [14]

Type of Operation	Acceleration (G)	Duration (Seconds)
Elevators: average in "fast service"	.1-.2	1-5
comfort limit	.3	
emergency deceleration	2.5	
Public transit: normal acceleration and deceleration	.1-.2	5
emergency stop braking from 70 m.p.h.	.4	2.5
Automobiles: comfortable stop	.25	5-8
very undesirable	.45	3-5
maximum obtainable	.7	3
crash (potentially survivable)	20-100	.1
Aircraft: ordinary take-off	.5	10
catapult take-off	2.5-6	1.5
crash landing (potentially survivable)	20-100	
seat ejection	10-15	.25
Man: parachute opening - 40,000 ft.	33	.2-.5
6,000 ft.	8.5	.5
parachute landing	3-4	.1-.2
fall into fireman's net	20	.1
approximate survival limit with well-distributed forces (fall into deep snow bank)	200	.015-.03
Head: adult head falling from 6 ft. onto hard surface	250	.007
voluntarily tolerated impact with protective headgear	18-23	.02

BIOGRAPHICAL SKETCH

William R. McKenney entered the United States Army after graduation from West Point in 1954. He has served in Artillery, Medical, Airborne, and Aviation units since his appointment in the Regular Army. A member of the Army Medical Service Corps, Lieutenant Colonel McKenney served combat tours in the Dominican Republic and Vietnam with helicopter aeromedical evacuation units. He is a member of the Aerospace Medical Association, American Institute of Astronautics and Aeronautics, American Institute of Industrial Engineers, and Association of the United States Army. Colonel McKenney was assigned as Liaison Officer to the "AvSER" Facility of Dynamic Science in Phoenix when he wrote this report to fulfill requirements for a Master of Science in Engineering degree at Arizona State University.